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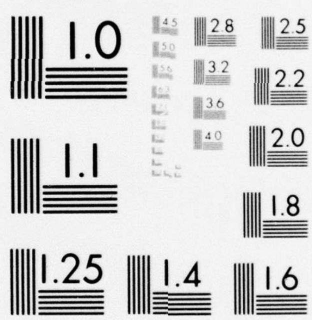

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Report # - C033-42034

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Prepared by

General Electric Company
Heavy Military Electronics Department
Syracuse, New York

Technical Memo

Array and Transducer

Suitability of a Receive Array Using Small Elements (U)

CONFORMAL/PLANAR ARRAY SONAR PROJECT

25 October 1966

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Contract NObsr 93022
Project Serial Number SS-048-00
Task 8189
(GE Requisition Number EH-88157)

Prepared for

690425-0260

Navy Department, Naval Ship Systems Command
U.S. Navy Electronics Laboratory
San Diego, California

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Suitability of a Receive Array Using Small Elements

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ABSTRACT

The use of a separate array of small transducers for receive modes in the Conformal/Planar Array Sonar System was investigated.

The investigation indicates that the benefits provided by using the small element array appear to be outweighed by the increased cost and complexity.

Suitability of a Receive Array Using Small Elements

SECTION I

INTRODUCTION

Recently, consideration has been given to the use of a separate array of small transducers for receive modes on C/PAS. The primary reason for reopening the subject has been the predicted marginal acceleration response of the large active elements, but additionally, other arguments have been presented in favor of this array.

The General Electric Company considered this type of configuration some time ago; at that time, it was decided that the incremental gain provided by an array of small elements did not warrant the increase in cost and complexity. It is felt at this time that all things considered, there is insufficient reason to change the mainstream approach.

In the following section a discussion is presented listing the pros and cons of adding the small array. This is followed by a detailed technical discussion of the points in question.

SECTION II

POINTS OF DISCUSSION

The points of discussion regarding an additional receive array are given as follows:

1. Acceleration Response:

   In defense of an additional array, it is claimed that in the receive mode, the elements used for the active array would be acceleration limited.

   In rebuttal, it is claimed that tests taken with larger elements indicate that slight modification in mounting would result in satisfactory performance, and that acceleration response of small elements is not necessarily better.

2. Frequency Response:

   Proponents of an additional array contend that the response of small elements is more uniformly flat, therefore resulting in a net passive gain. Also, it is claimed that it is easier to achieve velocity control with smaller elements.

   The counter arguments are that:

   (1) the noise taper can be matched with sufficient accuracy to achieve acceptable gain

   (2) that interelement deviations in amplitude should not result in significant loss in array sensitivity

   (3) that velocity control is adequate with large elements, and is a function of adjoining boundary conditions as well as element size.

   Additionally, it is claimed that interference from other sonar will degrade high frequency passive operation.

3. Angular Sensitivity:

   It is claimed that there is an array performance gain with the small elements over the large elements since the latter become too directional at the higher frequencies.

It is also claimed the angular response difference is not a step-function and that performance is acceptable with the active elements.

4. Flow Noise:

It is claimed that flow noise response is better with the active elements; however, more smaller elements can tend to equalize this difference.

5. Equipment Considerations:

It is claimed that there are implementation advantages with either system.

A detailed discussion of these points is presented in Section III. It will be concluded, from the basis of these discussion points, that there is little reason for adding a separate receive array.

SECTION III

DETAILED TECHNICAL DISCUSSION

A. ELEMENT RESPONSE TO ACCELERATION

1. Introduction

With the proposal that the transmitting array on C/PAS be supplanted in receive and passive modes by an array of small elements, it was argued that acceleration response would likely be the limiting factor in receive operation, and that smaller elements are naturally less sensitive to acceleration than large elements (i.e., response is proportional to mass).

However, this argument is incomplete. First, the mass of the element involved is certainly related to the acceleration response, but only in some complex fashion. Additionally, response data indicates that with careful design, the elements would not be acceleration limited above 10 knots.

To substantiate this line of thinking we will present the following information below:

(1) Experimental Data

This data indicates that typical elements operating under anticipated acceleration drive conditions give what would be marginal acceleration isolation for C/PAS, but that minor changes should rectify this problem (since these elements were not designed for C/PAS).

(2) Element Model

A model of the element-can-stave is presented.

2. Experimental Data

Measured acceleration response is shown in Figure 1 for a large (SQS-26-type) element. The measurement conditions are indicated on Figure 1. For reference, the element sensitivity is provided in Figure 2. Similar information is given for the elements provided by General Electric for the PURVIS I experiments in Figures 3 and 4. In Figure 5, a comparison is made between acceleration and interference, and self noise at various speeds for the large element, and again in Figure 6 for the small element. For the case shown, the small element is less sensitive to

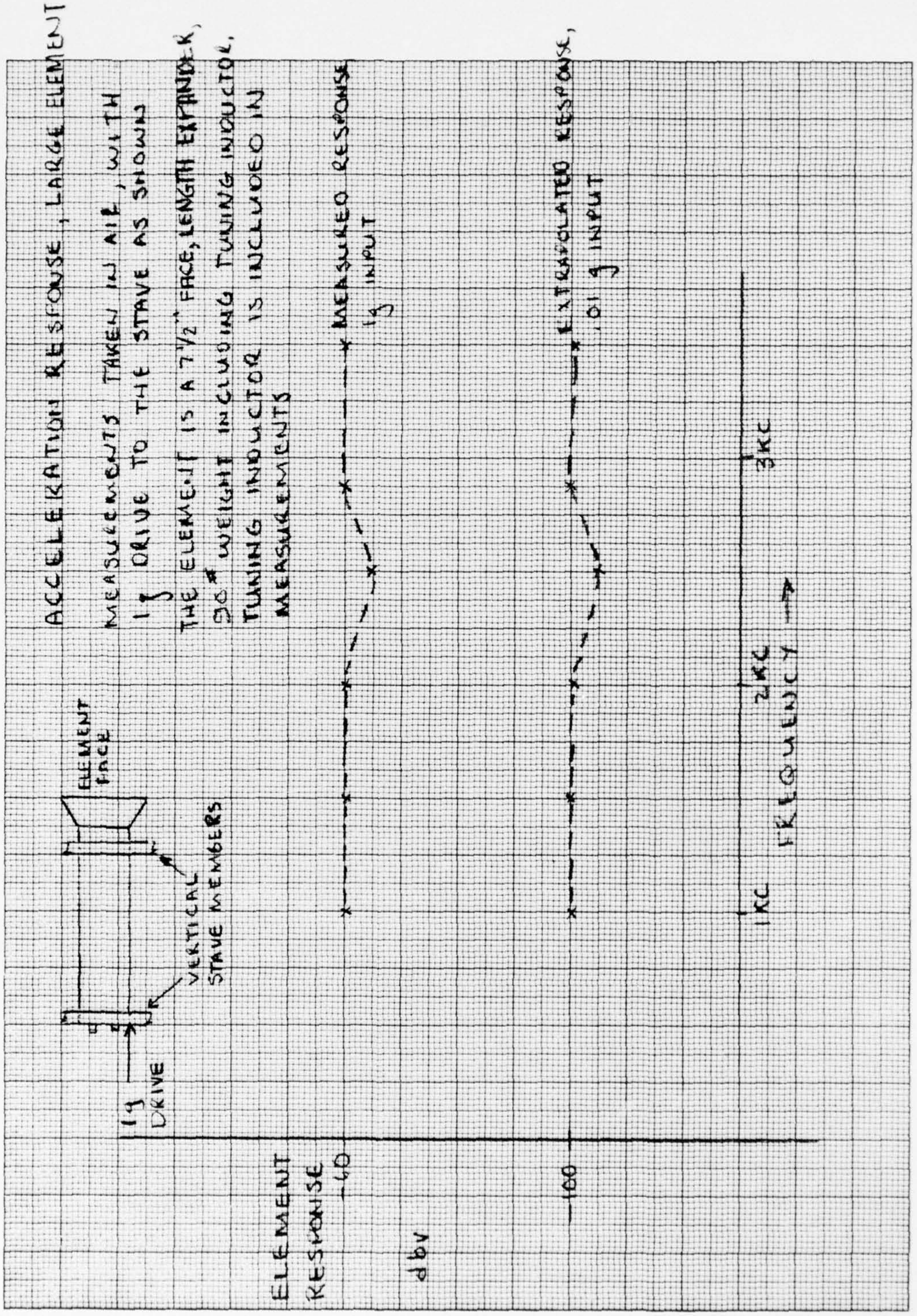


Figure 1. Acceleration Response, Large Element

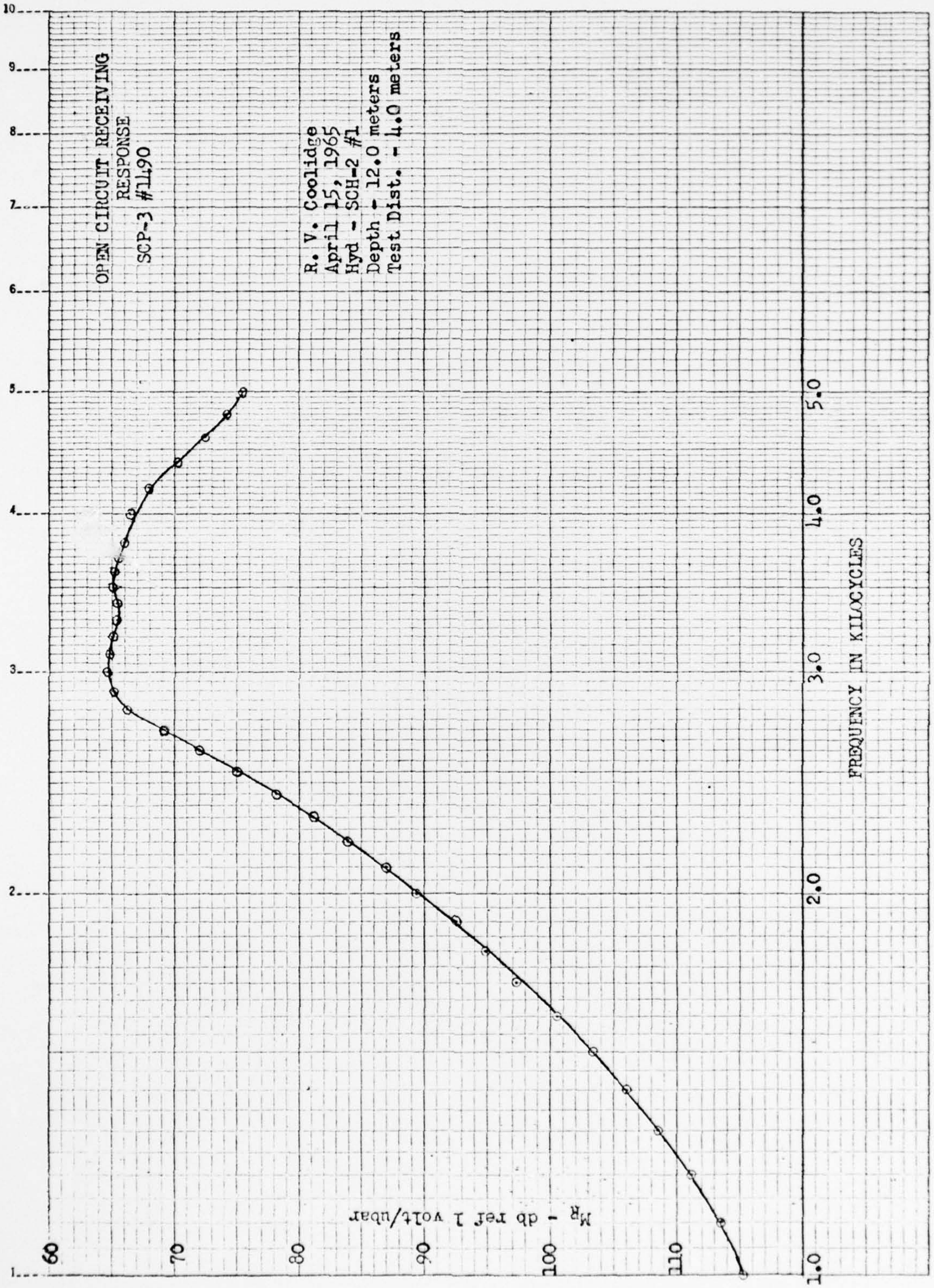


Figure 2. Open-Circuit Receiving Response

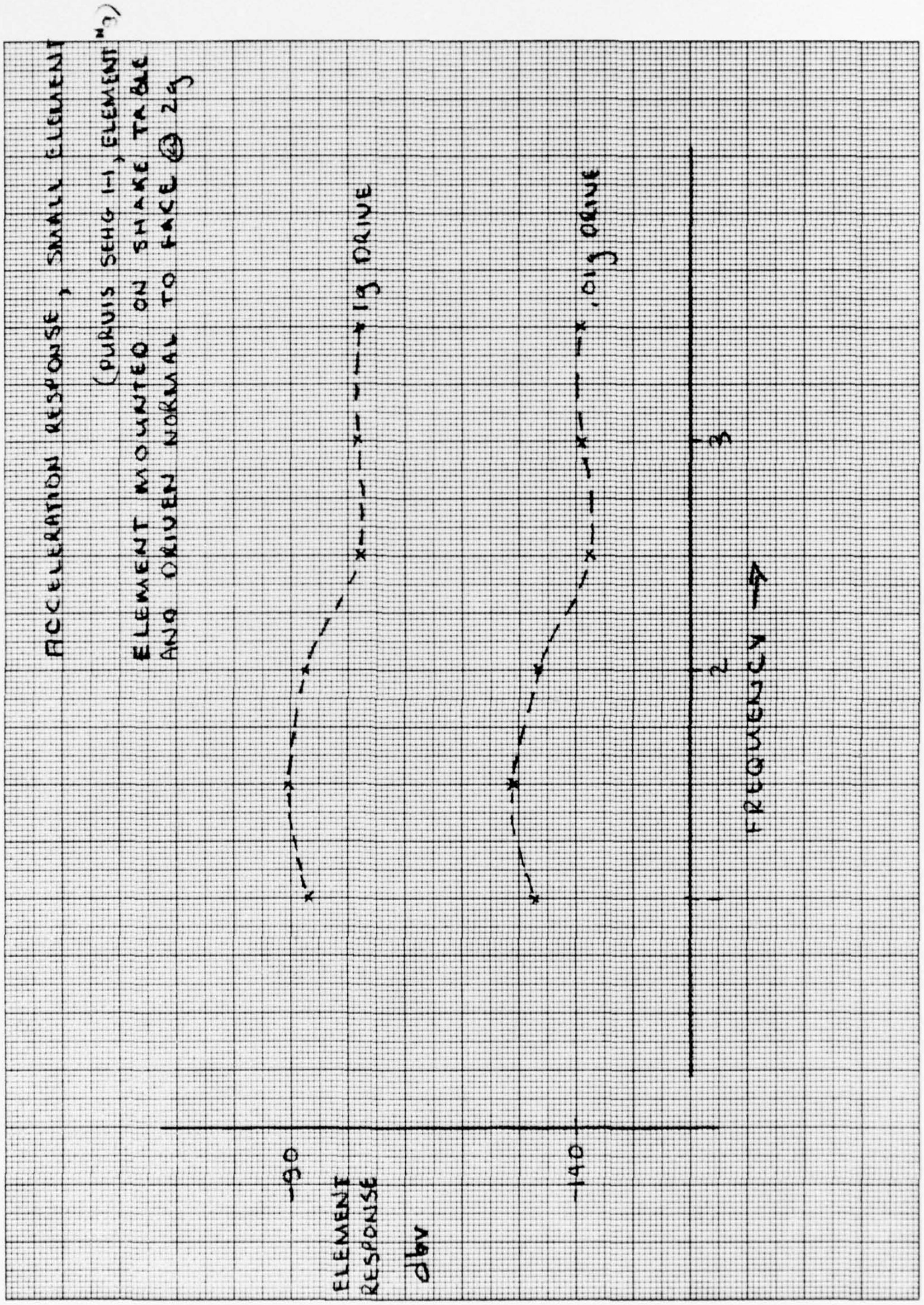


Figure 3. Acceleration Response, Small Element

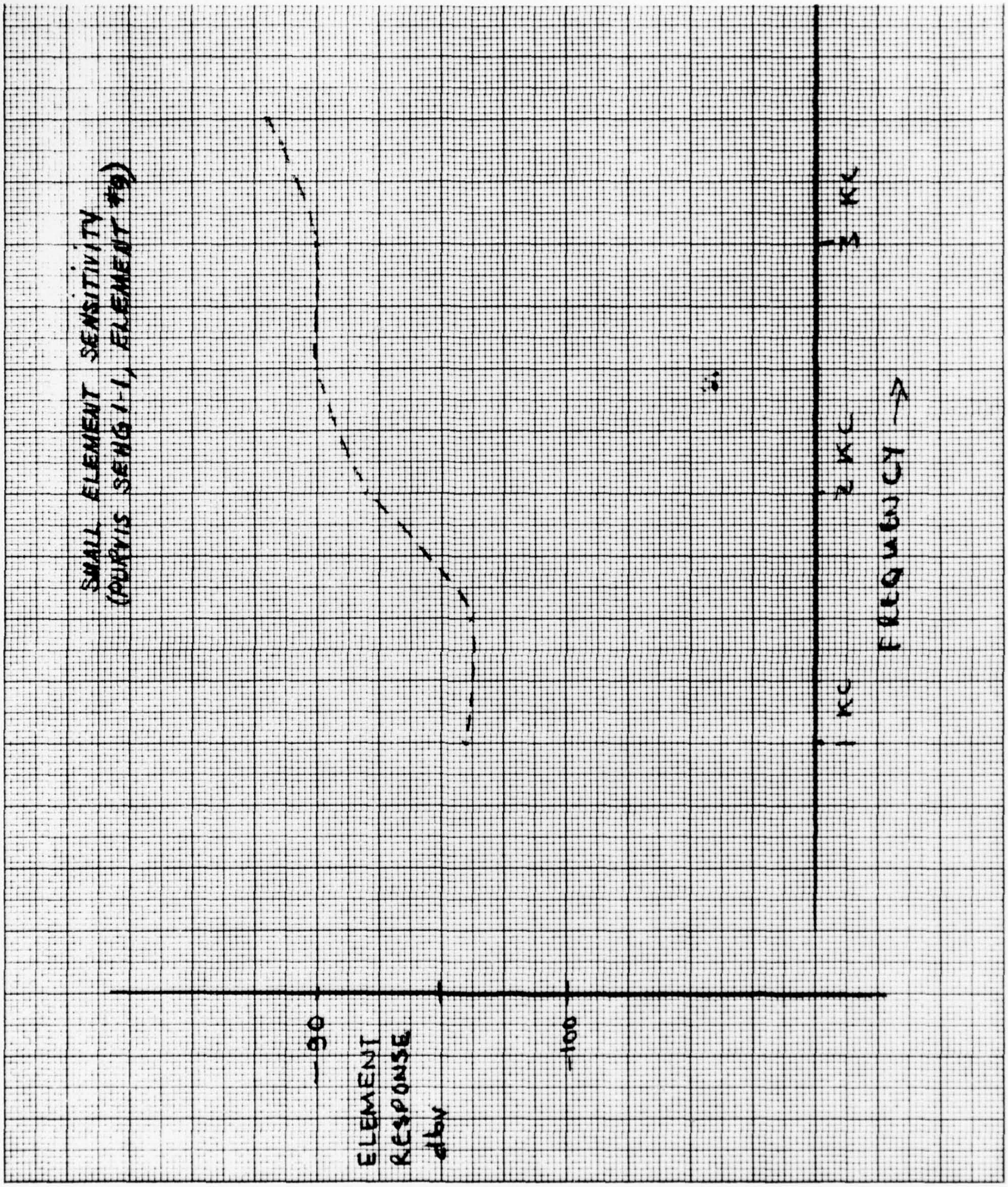


Figure 4. Small Element Sensitivity

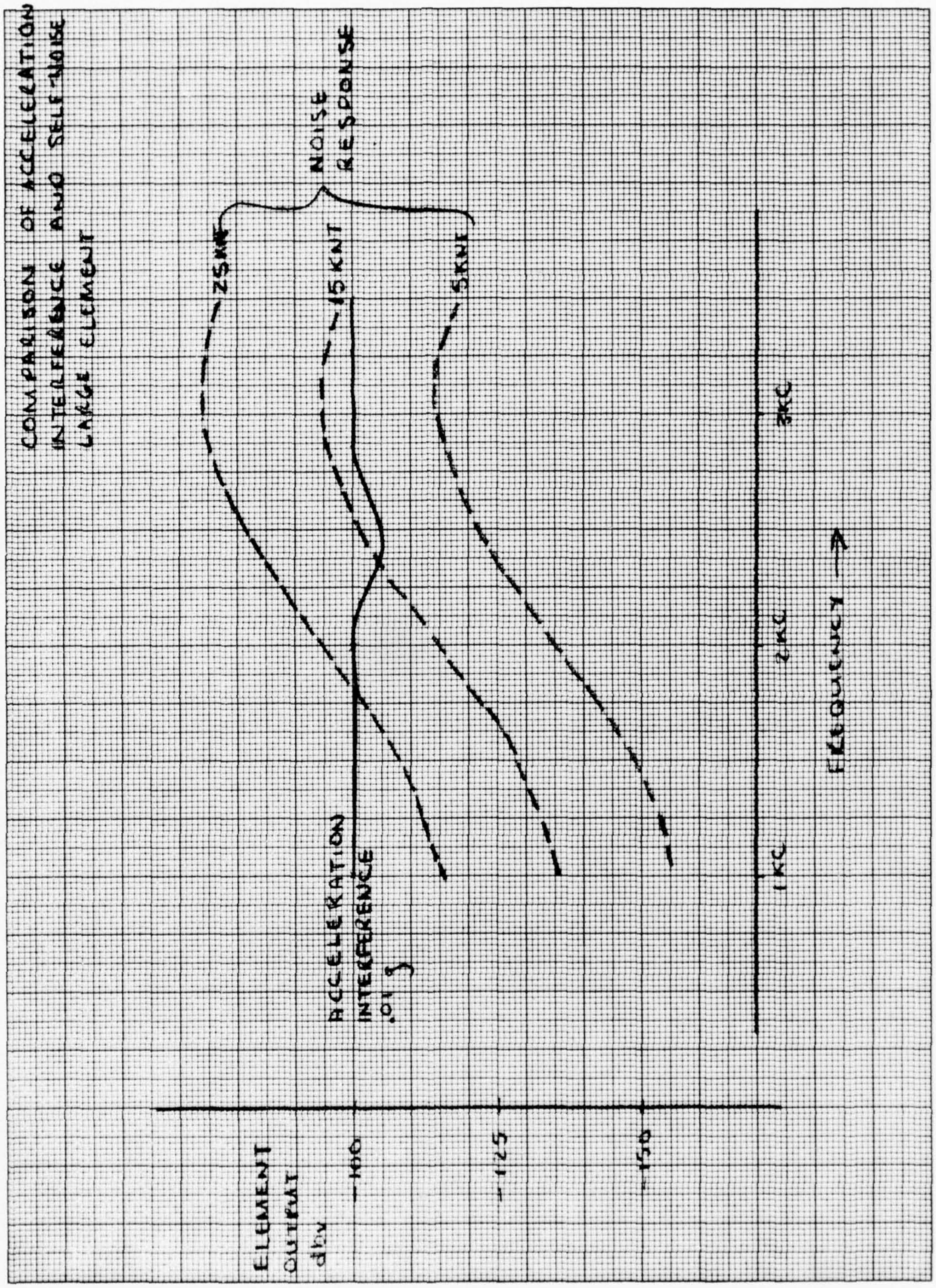


Figure 5. Comparison of Acceleration Interference and Self-Noise, Large Element

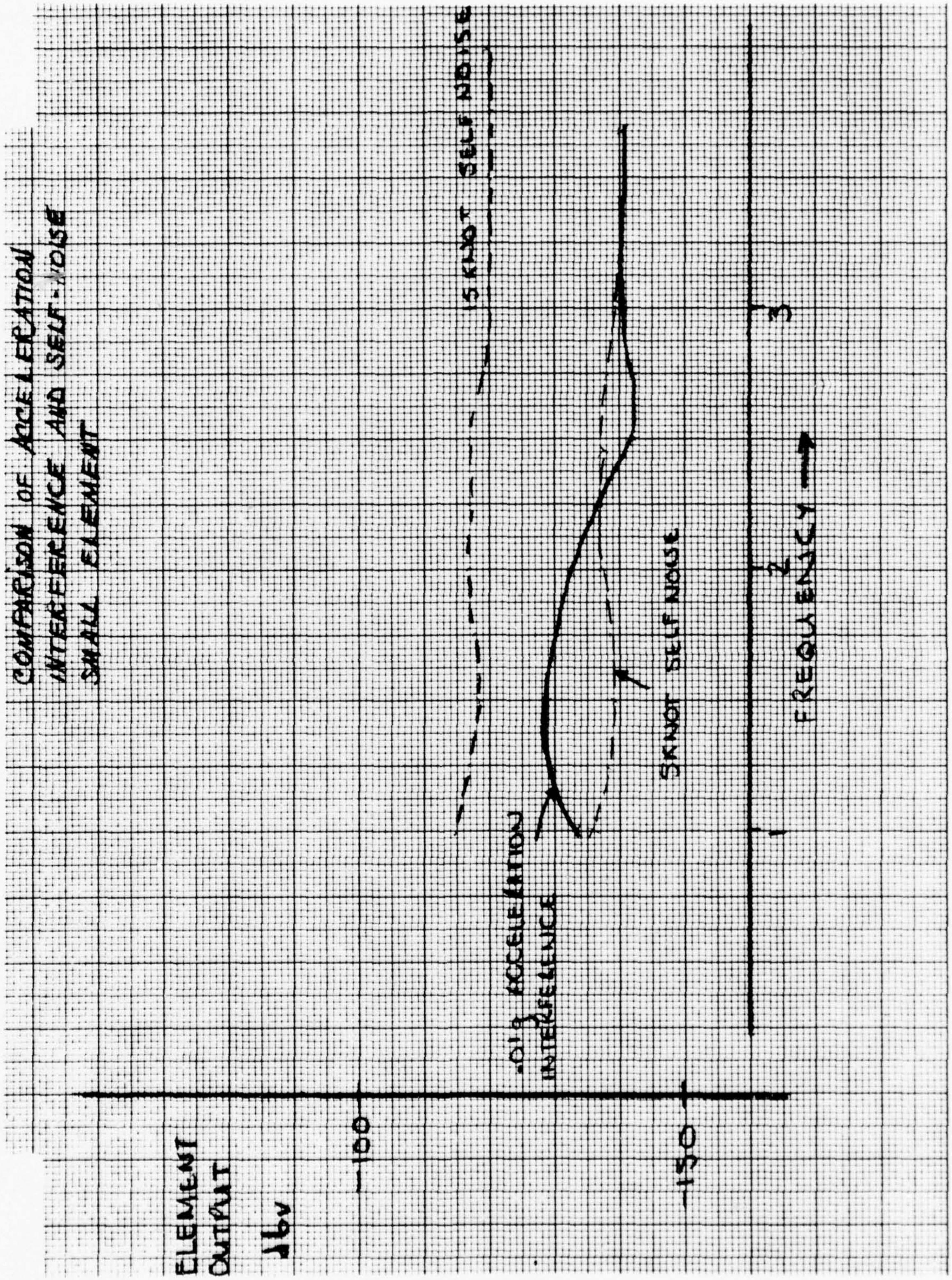


Figure 6. Comparison of Acceleration Interference and Self-Noise,Small Element

acceleration than the large element, but this need not necessarily be so (i.e., the small element was not subject to shock tests).

3. Mathematical Model of the Can

The particular network configuration shown in Figure 7 depicts General Electric's can design. For this scheme, the acoustic release and back-up plate are connected in cascade with the tail mass. The portion of the can tubing between the head and tail masses is attached in series with the element, acoustic release, and back-up plate. The acoustic release at the head mass is attached in cascade with the can tubing. The transformer and its housing are connected in cascade at the back-up plate end of the series circuit.

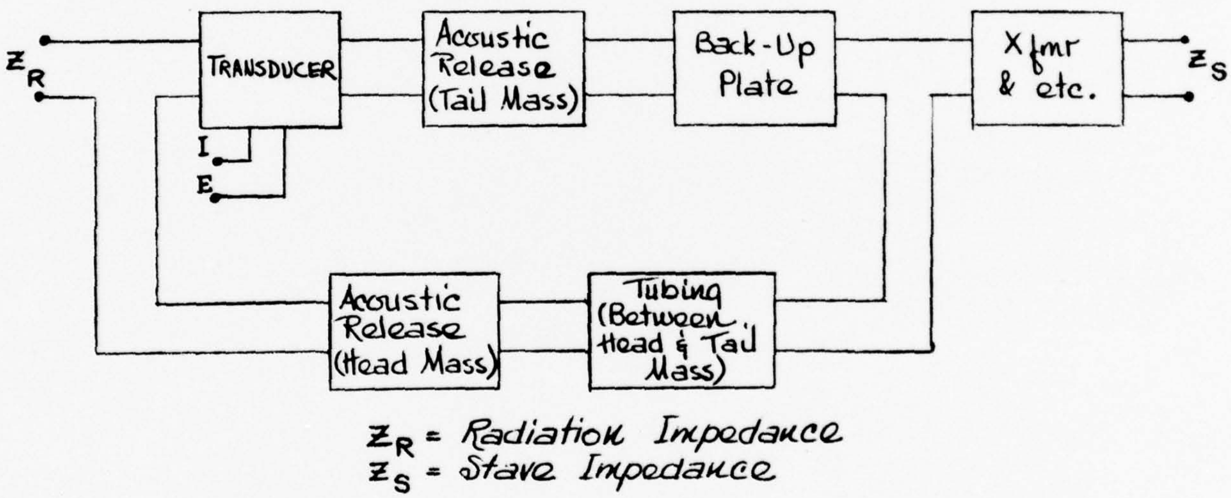


Figure 7. Equivalent Circuit for Transducer and Can

The mathematical model of the complete transducer is a three port network as shown in Figure 8.

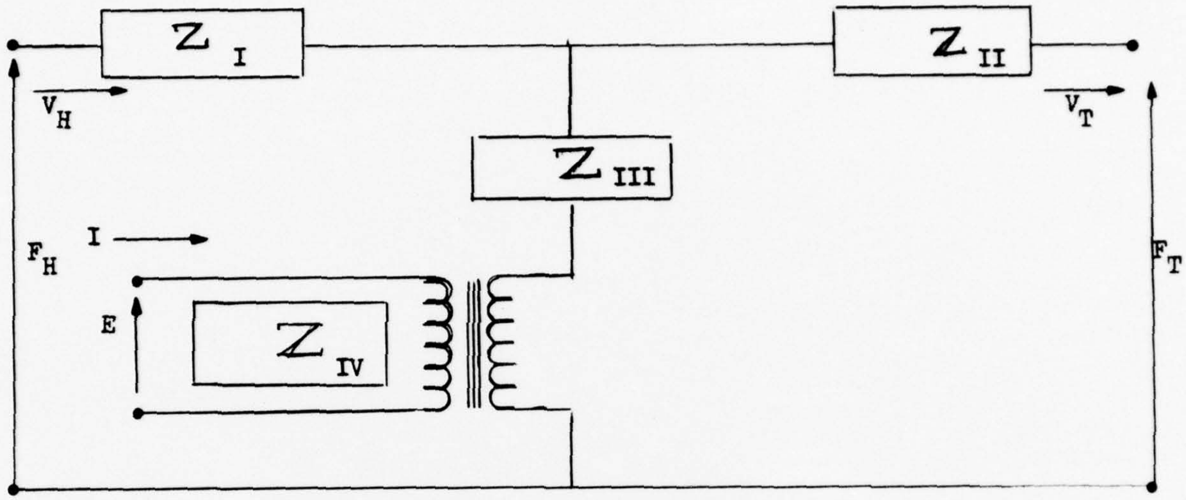


Figure 8. Equivalent Circuit For Transducer

To this network the equivalent circuit of the can is added. Each component of this equivalent circuit is passive and can be represented by a T-network.

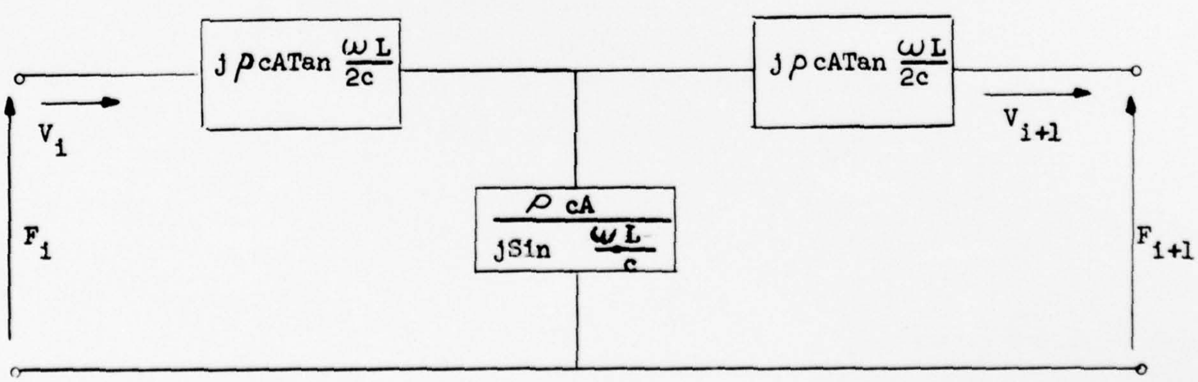


Figure 9. T-Network

By proper substitution of the T-networks into Figure 7, the model of the element and can is complete. (See Figure 10.)

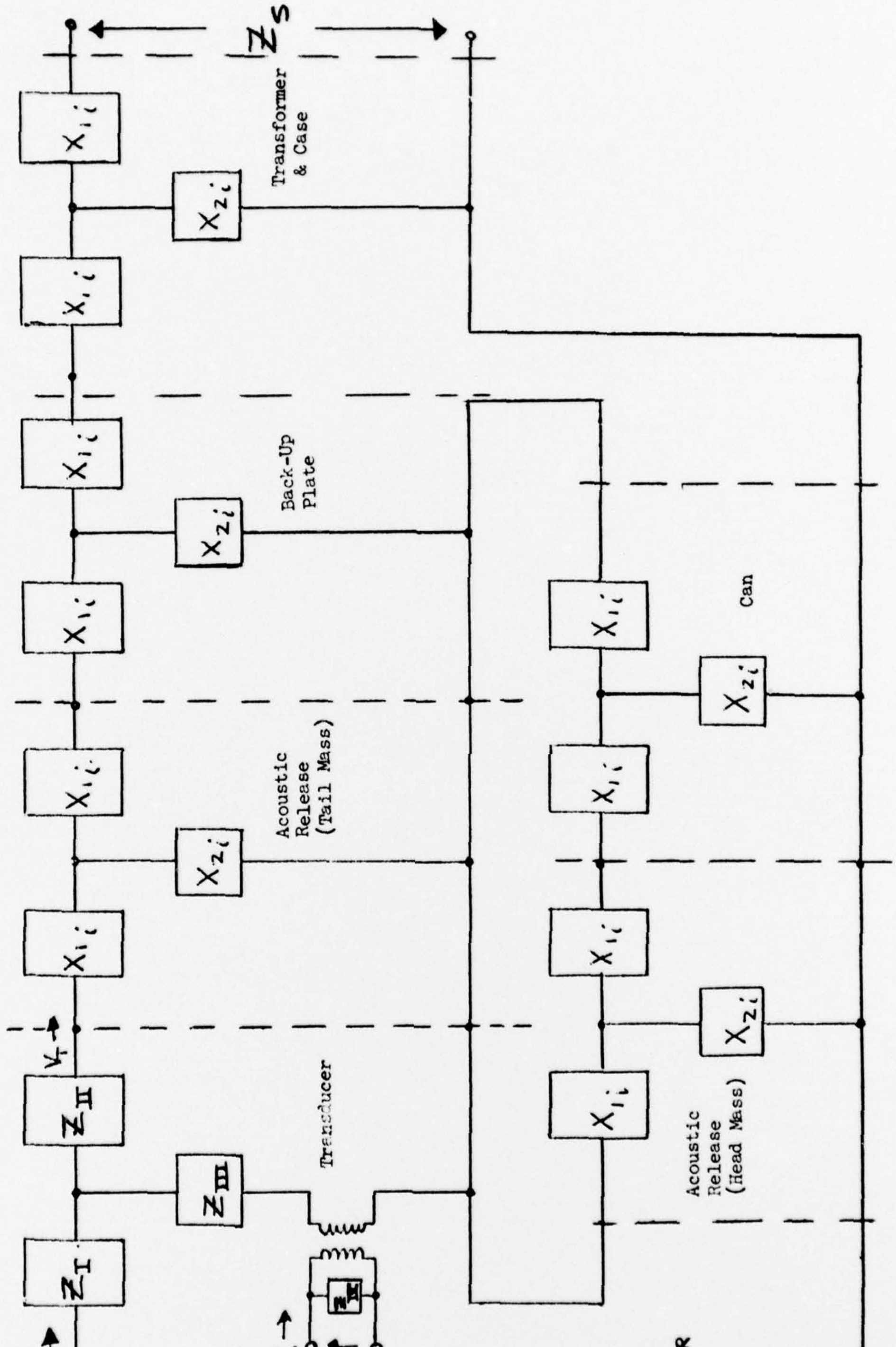


Figure 10. Equivalent T-Network Transducer and Can

Examining each of the network components individually, would lead to the conclusion that both of the acoustic release networks could be simulated by a single capacitor, as could z_s, since these represent physically small, high compliance devices.

In any event, this model would certainly lead to the conclusion that the relationships between various portions of the element are not simple, and that the problem needs some detailed study in order to arrive at a design that is sound from the standpoint of vibration.

4. Conclusion

The problem, then, should be resolved during the natural course of element and array design with the use of the model presented.

Close examination of Figure 10 shows that the model of the element in the can is very similar to the mathematical model of the transducer. That is, if we replace the A-matrix of the compacted ceramic with the A-total matrix of the transducer and consider the components of the can as being equivalent to end caps, tail masses, and stress rods, we can use the present transducer analysis computer program (TACP) to analyze the can. This modification of the TACP requires very little programming effort. The only major change in the program is to eliminate the subroutine that calculates the A-matrix for the compacted ceramic and input the A-total matrix for a transducer in its place. The only other modification would be to change the nomenclature in the printout; i.e., "stress rod" would be replaced by "can tubing", etc. The validity of this model is dependent upon two assumptions.

(1) The can does not radiate any energy.

(2) Each component is represented by a distributed parameter mathematical model.

For components such as onion skin paper release, the distributed parameter model may not give an accurate description of the transfer characteristics of the material. For these components a lumped parameter model (as shown in Figure 11) can be used.

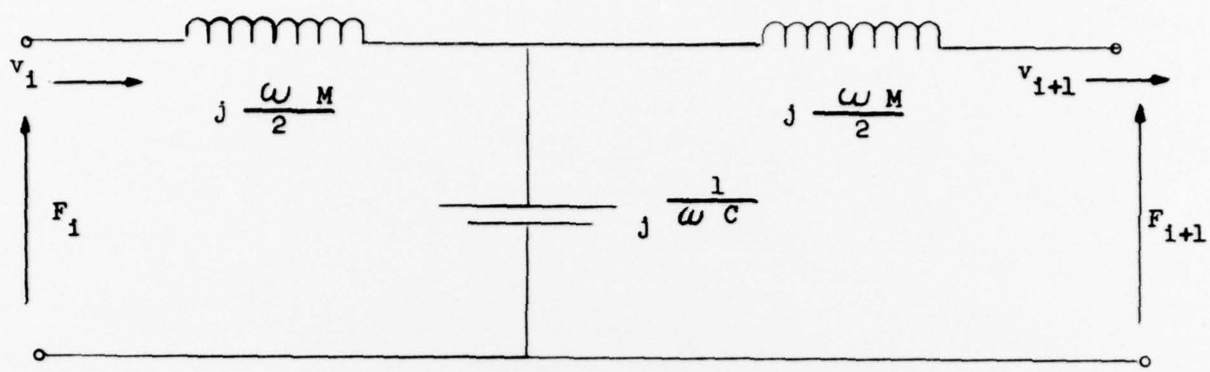


Figure 11. Lumped Parameter Model

The mass and compliance of the release material can be determined experimentally. The compliance of the material can be determined from a stress-strain curve experimentally determined on a Universal Tester An example of the calculation of the compliance for 30 sheets of onion skin paper is shown below.

When the element is bolted into the can, there is a static force of between 450 to 650 pounds across the release material. Over this range the slope of the stress-strain curve is relatively constant. The slope of the curve (Young's Modulus) for 30 sheets of paper is:

$$Y = \frac{(T_2 - T_1)}{(2 - 1)} = \frac{T}{\ } = 21.6 \times 10^4 \text{ psi}$$

Compliance is defined as:

$$C = \frac{t}{YA} \quad \left(\frac{\text{inches}}{\text{pound}}\right)$$

where: t = thickness in inches

A = area in square inches

Y = Young's Modulus in psi

The mean thickness of 30 sheets of paper is 5.5×10^{-2} inches and the area is 3.7 inches. For these values of compliance of the paper is 6.9×10^{-8} in/lb or 1.01×10^{-7} M/N. Although it is not obvious from the magnitude of the numbers, this material has a very large compliance and presents a very low impedance to the velocity at the tail mass. In short, the onion skin paper is an excellent acoustic release material. The lumped parameter model is valid since the wavelength for the release material is very much larger than the thickness of the material.

Since the acoustic release has such a large compliance, the velocity of the can will be several orders of magnitude smaller than the head or tail velocity. Thus, the assumption that the can does not radiate energy is valid.

B. ELEMENT FREQUENCY RESPONSE

1. Effect of the Element Frequency Response on the Passive System Gain

In order to determine the possible effect of frequency response on the passive gain, an analysis was performed using an available computer program to compute passive system output signal-to-noise ratio and optimum pre-emphasis characteristic versus range. The program takes into consideration - target radiated noise, self and ambient noise, directivity of the array, propagation over several paths, transducer response and pre-emphasis characteristics. Nominal values were used for all of these parameters except the transducer response characteristic. (See Appendix D C/PAS Second-Cut Signal Processing Report.) The responses used for this analysis are shown in Figure 12.

Figures 13 and 14 were plotted from the printout of the program and the results and conclusions were drawn from consideration of these figures.

Figure 13 shows that the optimum pre-emphasis characteristic for the passive system is different for the transducer (7.5 in. by 7.5 in.) and the hydrophone (2 in. by 2 in.). In fact, the pre-emphasis for the transducer appears to be rather hard to achieve exactly.

However, from Figure 14 we see that even for the unmatched case there is very little loss in passive system gain in the low frequency band.

Thus, it seems safe to conclude:

(1) The passive gain in the low frequency band is not critically dependent on matching the pre-emphasis filter exactly.

(2) It should be possible to match the pre-emphasis filter sufficiently to achieve acceptable gain with either the large transducer or the small hydrophone element.

2. Phase Tracking Problem

The problem of deviation in amplitude response causing phase deviations was examined, (this being emphasized when elements are operated above resonance) and should not be significant. At a given frequency, the correlation function is perturbed as in

$$F(\tau) = A \cos(\tau + \phi)$$

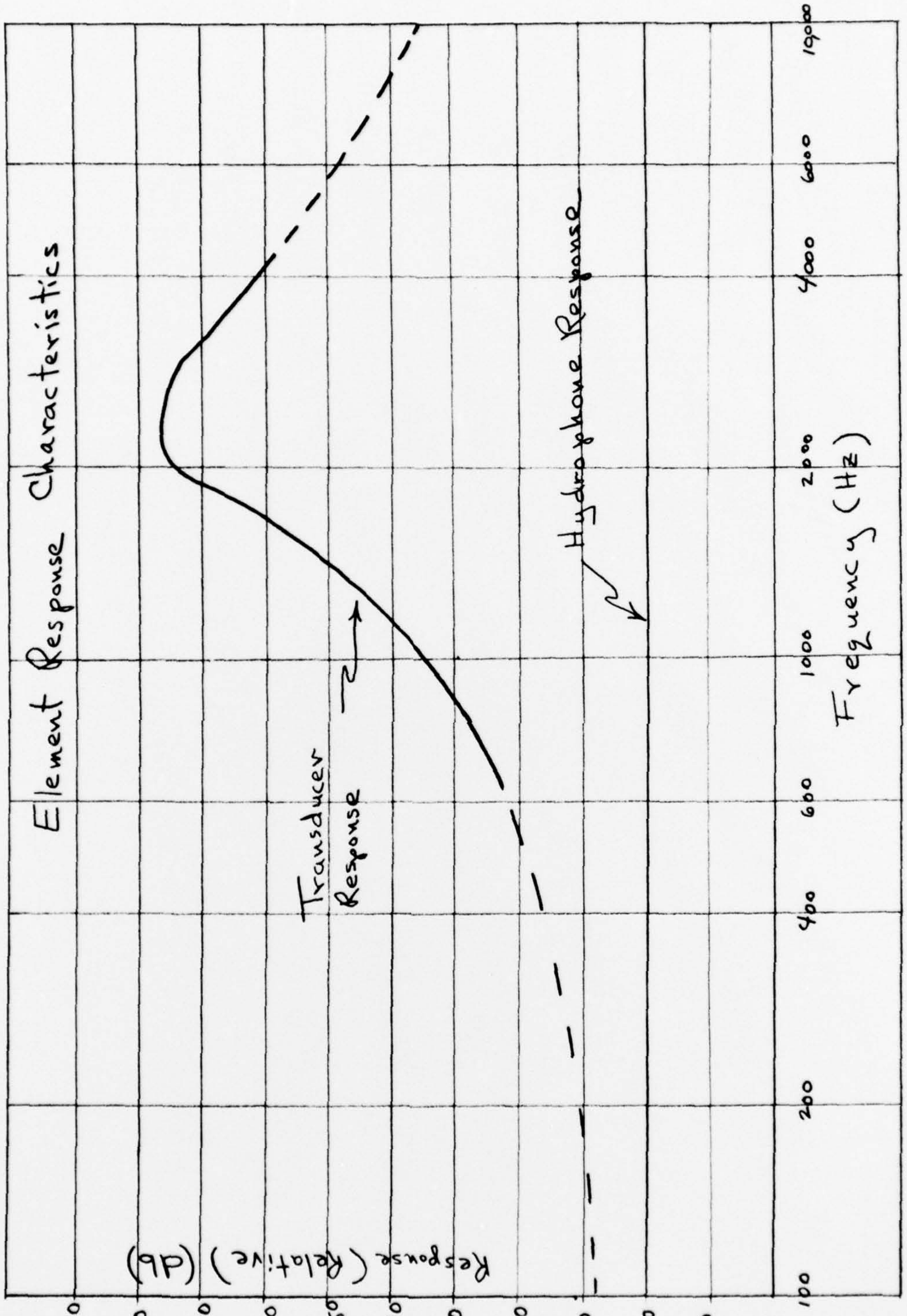


Figure 12. Element Response Characteristics

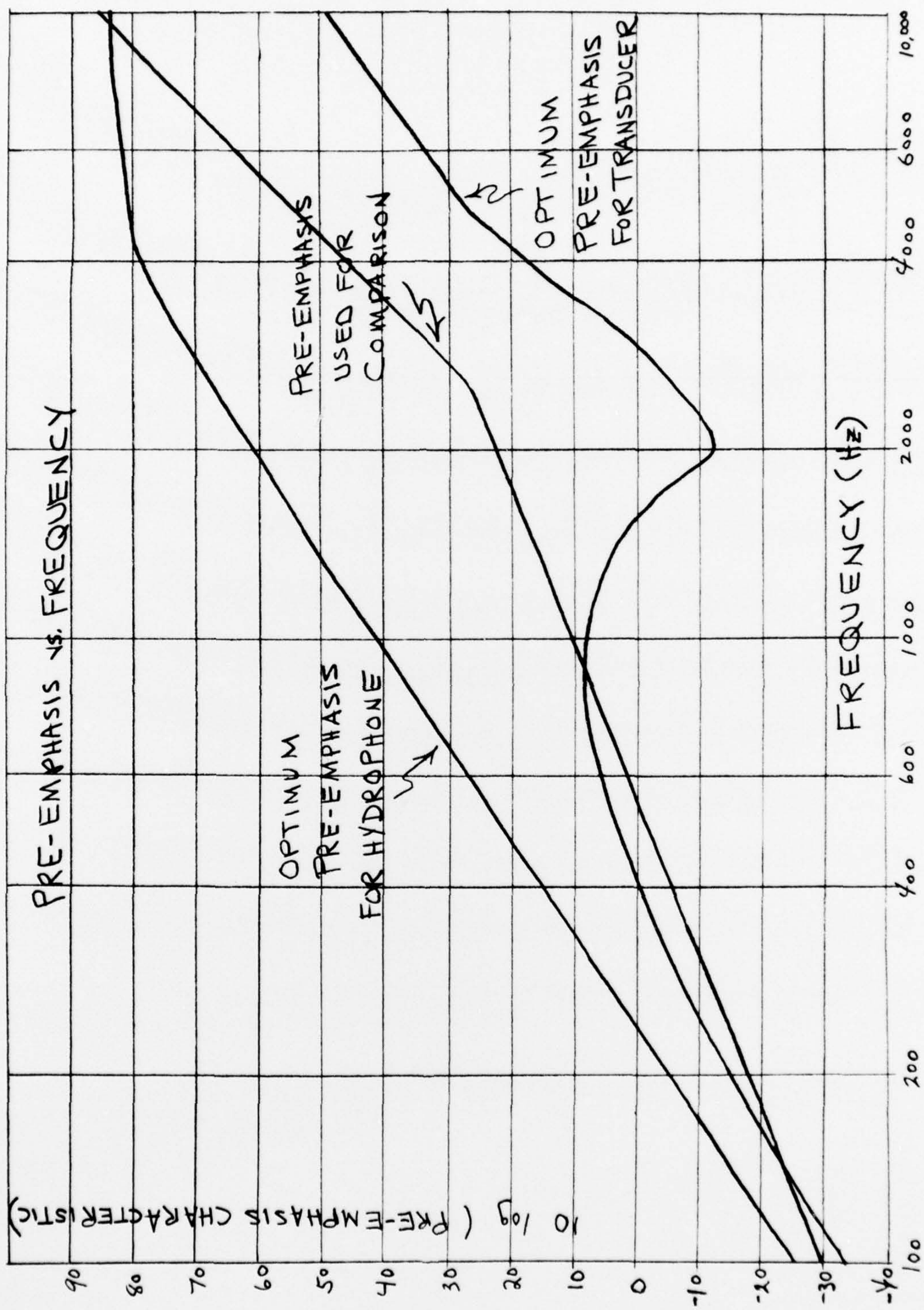


Figure 13. Pre-Emphasis vs Frequency

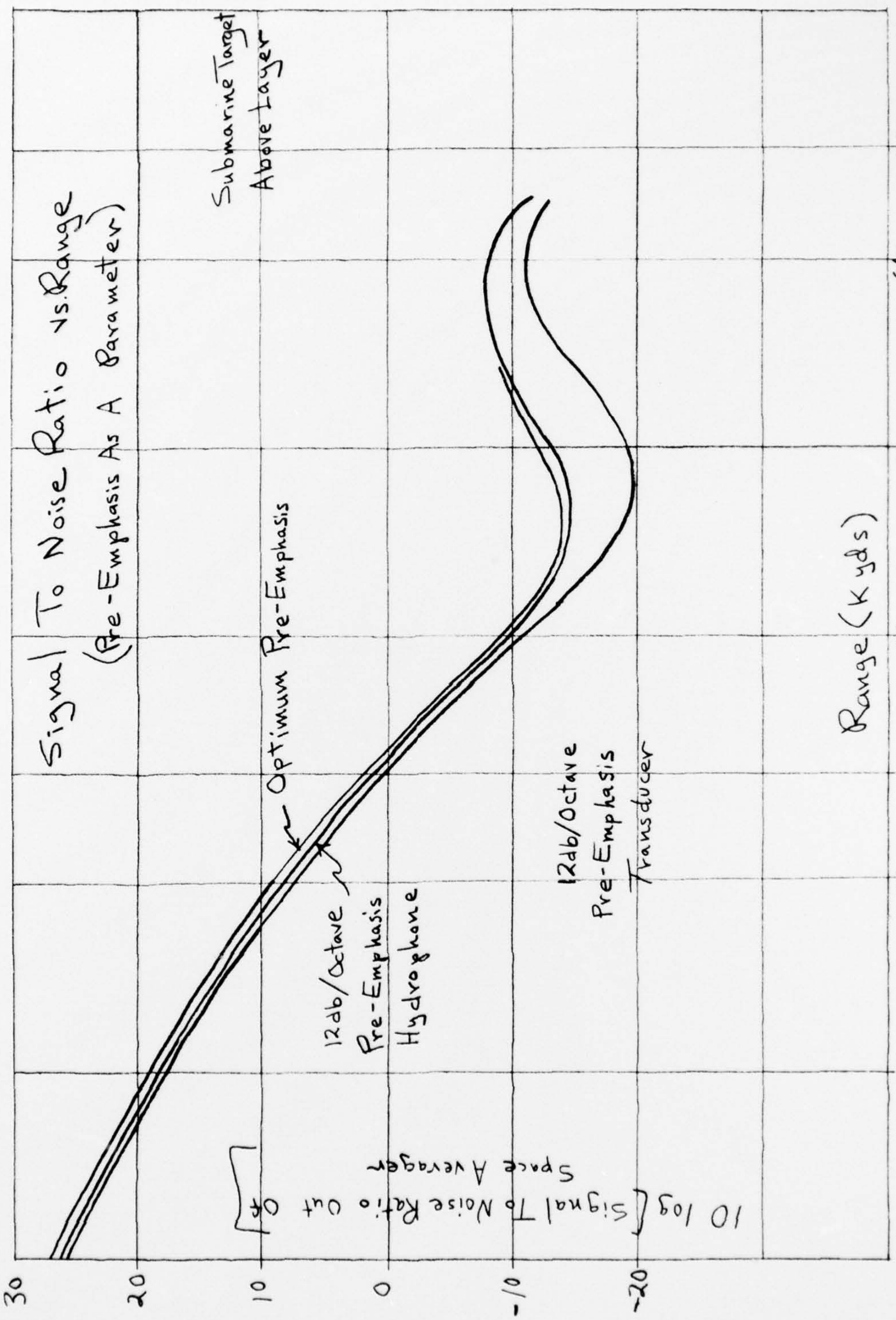


Figure 14. Signal-To-Noise Ratio vs Range

Where ϕ = the phase deviation introduced; thus, the correlation function can be modified to account for ϕ, since it is known, or ϕ can be disregarded if it is less than, say 10°.

3. Preliminary Analysis of the Effect on C/PAS Passive Performance of Interference From the SQS-26 Active Sonar

The purpose of this analysis was to determine if the SQS-26 will degrade the C/PAS passive sonar (in the 3 to 4 kHz band) when the two sonars are operating in the vicinity of each other.

The interference problem was considered in two parts:

(1) The interference arrives on the main lobe of the beam of interest.

(2) The interference arrives in a side lobe of the beam of interest.

Noise Levels

However, first we consider the relative background and self-noise levels and interference levels.

a. The background and self-noise levels are assumed to be -30 db//dyne//cm^2 in a one-cycle band. The directivity is assumed to be 30 db and the bandwidth is 3 to 4 kHz or 1000 Hz. This gives a total noise power of -30 -30 + 30 = -30 db in the band of interest.

b. We also assume that the SQS-26 to be operating in ODT mode with a level of 130 db//dyne//cm^2 at ranges which give one way propagation losses of from 60 db to 120 db. Also the maximum side lobe reduction in level is assumed to be -40 db. Using these assumptions the interference levels are +70 db to +10 db for signals arriving on the main lobe of the beam and +30 to -30 db for signals arriving way off of the main lobe of the beam.

Thus, the interference to noise ratio will vary from +100 db to +40 db on the main lobe and from +60 db to 0 db off of the main lobe.

Space Averager

For interference both on and off of the main lobe, the part of the passive system most influential in reducing interference is the space averager. The space averager determines a measure of the mean level of noise by averaging the inputs from adjacent beams. Then it subtracts this measured mean from the output of the beam of interest. Any change in mean level is used to determine if a target is present in the beam of interest.

The space averager acts as a variable threshold device which varies the threshold with changes in noise level and with changes in angle.

For high level interference arriving on the main lobe there is a good chance that all sections of the space averager will contain the largest possible number and that the output will be very small after averaging and subtracting. In effect, this reduces the receiver sensitivity to zero. For low level interference all the sections of the space averager will not be full and the space averager will pass a false target indication to the time averager.

For high level interference arriving far off of the main lobe of the beam of interest, all sections of the space averager will contain interference arriving through sidelobes. Since the level of interference should be fairly evenly distributed in all sections of the space averager, the difference between the measured average interference and interference in the beam of interest should be small. Again, in this case, a loss in receiver sensitivity will result.

Loss in Sensitivity

The effect of a loss in receiver sensitivity is to reduce the integration time available for signals of interest. Since receiver gain is proportional to the square root of integration time a reduction of sensitivity for one second out of 10 will give a reduction in gain of 10 log $\left[\sqrt{\frac{10-1}{10}}\right]$ db.

Results

The results are more qualitative than quantitative due to the preliminary nature of this analysis.

The intereference will have two effects on the passive sonar:

1. In a beam or beams pointing at the interfering ship, a false target indication may be placed on the display.
2. For beams not pointed at the interfering ship, the sensitivity of the passive system will be greatly reduced during the time of reception of the interference. This reduction in sensitivity could produce a 0.25-db loss in total passive system gain for a interference time of 1 second out of 10.

C. EFFECT OF TRANSDUCER SIZE ON TOTAL ARRAY DIRECTIVITY

This analysis shows the effect of element size on the directivity of one side of the C/PAS V-array.

The receive beam pattern for an array of elements is made up of two components:

(1) an array factor (assuming the elements are isotropic receivers)

(2) a transducer factor (accounting for the directive response of the transducer).

The total array pattern consists of the product of factors one and two. If the pattern due to the transducer is much wider than that due to the array of isotropic receivers, the total directivity is approximately equal to that due to the array directivity, multiplied by the transducer response in the direction steered. This is the case for the C/PAS system since the ratio of array width to transducer width is at least 12 to 1.

Since we only desire the change in directivity as a function of element size, we need only calculate the transducer response pattern as a function of element size. The directivity of the array of isotropic sources will remain constant.

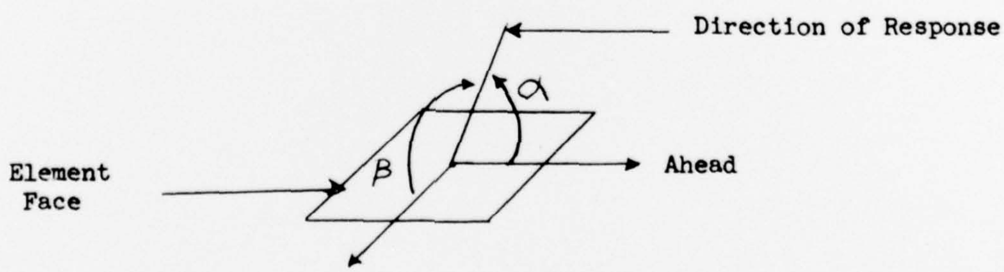
The response of a square transducer is of the form (see Horton, Fundamentals of Sonar)

$$\text{Response}(\alpha, \beta) = \left[\frac{\sin\left(\frac{\pi W}{\lambda}\cos\alpha\right)}{\frac{\pi W}{\lambda}\cos}\right]^2 \left[\frac{\sin\left(\frac{\pi W}{\lambda}\cos\beta\right)}{\frac{\pi W}{\lambda}\cos\beta}\right]^2$$

where: W = transducer width

λ = wave length

α and β are measured as shown in the sketch below



It is assumed that, (a) elements are mounted with their faces in the plane of the array and (b) the broadside to the array is 20° down from the vertical. Using these assumptions, the following values of α and β were determined.

Broadside to Ship	$\alpha = 90°$,	$\beta = 70°$
45° from Ahead	$\alpha = 45°$,	$\beta = 77°$
Ahead	$\alpha = 0°$,	$\beta = 90°$

Figure 15 showing loss in directivity was plotted using these values and varying the element width.

Figure 15 shows the effect of element width (square elements assumed) on array directivity for three azimuthal steering angles. Comparing the 2-inch and 7 1/2-inch elements for the worst case (ahead with respect to the ship and steered in in the surface duct) shows a 1.3 db directivity advantage for the 2-inch element at 2.5 kHz and a 3.7-db advantage at 4 kHz. Although it is not specifically shown in Figure 15, the 2-inch element has only a 0.3-db advantage in the 0.8- to 1.8-kHz passive band.

D. FLOW NOISE

In the element size, and speed ranges of interest here, the signal-to-noise ratio is a function of the total face area of an array, and doubling the face area increases the signal-to-noise ratio by 3 db(as shown in Figure 16). Thus, there is a decided disadvantage in using smaller elements, in that either S/N is less than what it would be with elements from the active array, or the array is more complex, since more elements are needed to achieve the same S/N.

E. COST OF ADDITIONAL RECEIVING ARRAY

An estimate of the cost in building the additional array of small elements is presented below:

1. Installation Cost

Probable cost is 1/4 the cost of the active array mounting costs.

2. Cost of Additional Elements

One array area = 8 x 150 feet = 1200 square feet.

Assume 1/3 λ spacing at mid-frequency.

(a) For coverage to 3 kc (2.5 kc mid-frequency) for active receiving and passive lower bands: Need spacing at 8-inch intervals $\therefore$ need approximately 2700 elements per array; or 5400 elements total. For element and cable cost of $100 each = $ 540,000

(b) For coverage to 4 kc[1], with 1/3 λ spacing to 4 kc, inter-element spacing of 5 inches, or 6400 elements per array, or 12,800 elements for both arrays. At $100/element including cable = $ 1,280,000

[1] "First Cut ESS Baseline System Description", TRACOR, Inc. report 66-517-C, page 5-4, September 1, 1966.

V-Array (one side only)
Beams Steered in Surface Duct

Square Elements
Width Equals Length

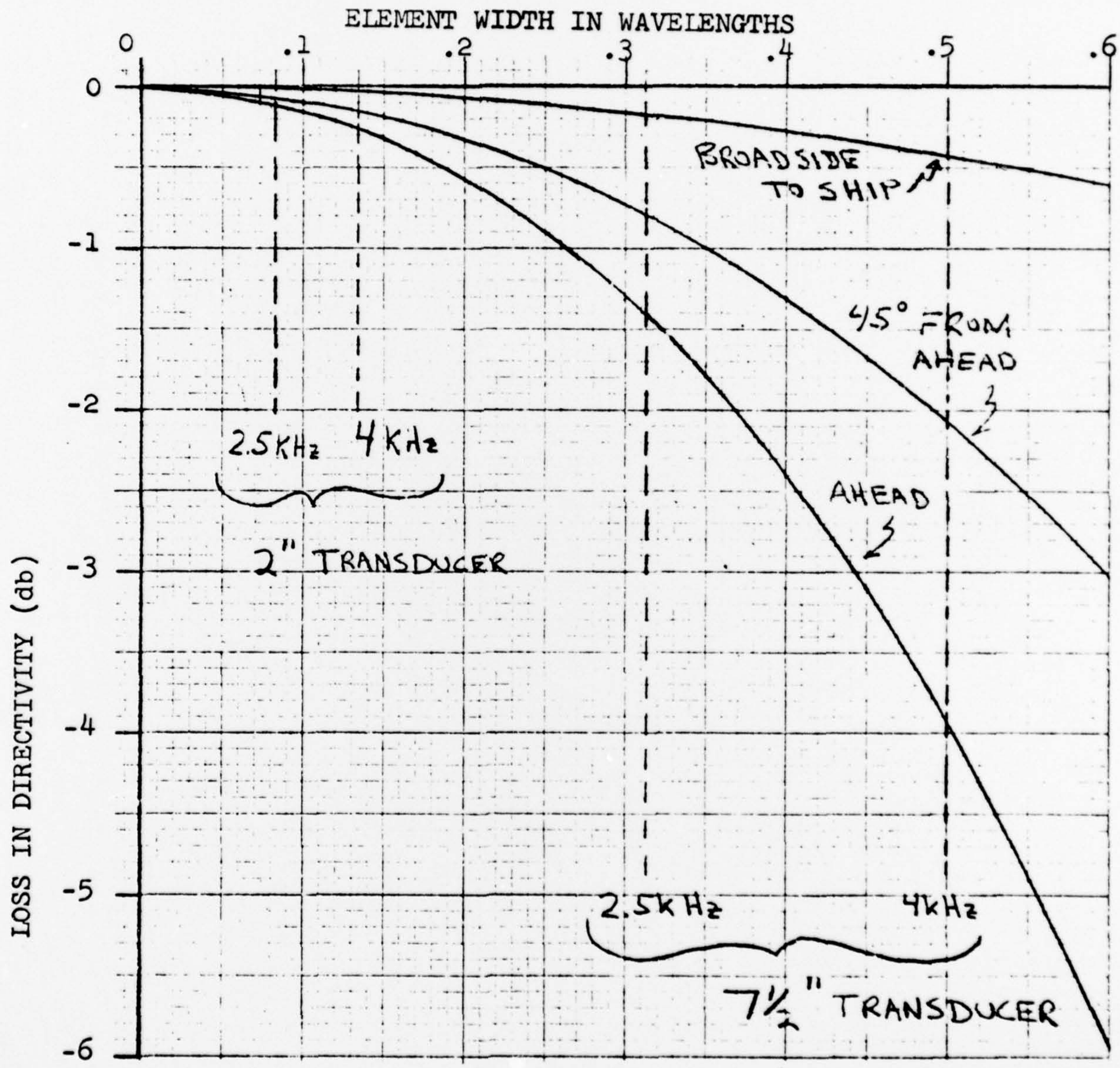


Figure 15. Effect of Element Width on Array Directivity for Several Steering Angles

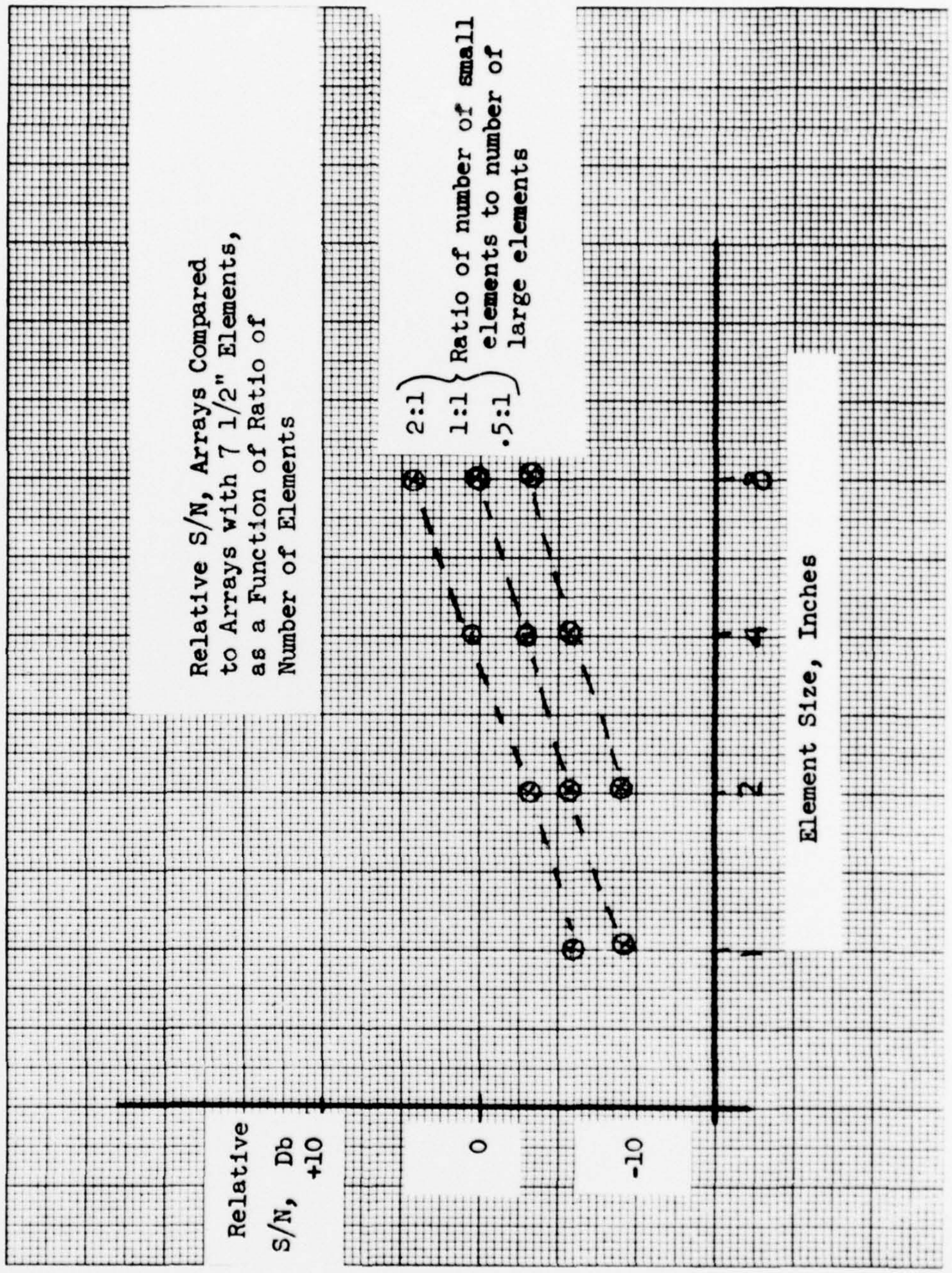


Figure 16. Relative S/N, Arrays Compared to Arrays With 7 1/2-inch Elements

3. Pre-Amps

Assuming that pre-amps are needed <u>at the transducers</u> to drive the cable lengths (approx. 100 feet per cable at 200 to 400 picofarads/10-feet length).

Cable encapsulated pre-amps at $200 each for 5400 =	$ 1,080,000
for 12,800 =	$ 2,560,000

4. T/R Devices

T/R devices may be needed to prevent damage to pre-amps for receive elements that are all in close proximity to transmit elements. <u>No</u> cost is included in this estimate at this time, since such a device will be required for the single array system.

5. Filters

Additional filters may, or may not, be required for each element. No costs are included for these.

<u>Total Costs</u>

(a) for lower passive bands + active receiving
$\approx$ <u>$1,600,000</u> per ship plus installation

(b) for capability to go to 4.0 kc (bottom of acoustic intercept band) plus (a) above
$\approx$ <u>$3,800,000</u> per ship plus installation

Thus, it appears that the additional cost incurred would be a significant portion of the entire system cost.